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CO_2 emissions from passenger transport

A comparison of international trends from 1973 to 1992

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This paper provides a comparative analysis of the changes in energy use and CO_2 emissions from passenger transport in nine OECD countries. Unlike most previous analyses, we base our analysis on a newly published international data set covering vehicle activity, passenger travel and fuel use by mode. We calculate how changes in activity, modal composition and the energy intensity of each mode contributed to changes in total energy use from travel in nine countries between 1973 and 1992. Increased travel activity and modal shifts boosted energy use, while reduction in modal energy intensities reduced energy use from automobiles in the USA and in air travel throughout the sample of countries. As a result, travel related energy use increased sharply in every country except in Denmark and the USA. Using these calculations, we then show how activity, modal shift and modal energy intensities affected CO_2 emissions from travel. Noting that the shifts of fuels within transport has been small, even counting shifts in the fuels used to produce the small amount of electricity used for passenger transport in every country, we find that increased activity and modal shifts also raised CO_2 emissions from travel in every country except the USA. We discuss briefly how a change in fuel mix, lower transport energy intensities, or even reduced levels of travel might lead to restraining or reducing CO_2 emissions from travel. Recalling that real prices for road fuels have fallen to near their 1973 levels while energy intensities remain level or are falling slowly, we foresee continued increases in travel, particularly in cars and airplanes, pushing emissions even higher. We ask what could restrain CO_2 in the future, should stringent restraints become a clear policy goal.

Keywords: CO_2 emissions trends; Passenger transport; Energy use

Since 1979, the International Energy Studies (IES) group at the Lawrence Berkeley Laboratory (LBL) has been studying how the structure and efficiency of energy use has contributed to changes in overall energy consumption in member countries of the Organization for Economic Co-operation and Development (OECD).

This work has led to a series of papers detailing energy use in major sectors and subsectors of nine countries (USA, Japan, Denmark, France, West Germany, Italy, Norway, Sweden and the UK) (Schipper *et al*, 1993a; Schipper *et al*, 1993b; Howarth and Schipper, 1991; Howarth *et al*, 1991). From this work, IES published the first international comparison of CO_2 emissions from the manufacturing sector of many of these countries (Torvanger, 1991), and more recently, the first analysis of emissions from the household sectors of these countries (Scheinbaum and Schipper, 1993). Our efforts at a factor decomposition of energy use are detailed in Schipper *et al*, 1992.

This study is the first to compare direct CO_2 emissions from passenger transport activity by mode in a large sample of OECD countries. In it we report on emissions and examine how the level of travel activity, the mix of travel modes (bus, car, etc), the energy intensities of those modes, and the fuel mix, including fuels used to generate electricity, affect CO_2 emissions over time. Further efforts will quantify emissions in freight activity, the service sector, and once again in the manufacturing sector. Finally, we will present a series of country studies in which we show how each of these factors affected all final energy uses in several of the countries we have studied.

Introduction

Over time, transport has played an increasingly important social and economic role in industrialized countries, linking people with each other and with goods and services. However,

Table 1 Carbon dioxide (CO_2) factors by fuel type in grams of CO_2 per megajoule of primary and secondary energy[a]

Fuels	kt CO_2 PJ
Engine fuels	Primary
Gasoline	67.50
Jet fuel (kerosene)	67.65
Diesel	69.41
Residual oil	75.27
Fuels for electricity	
Natural gas	50.52
Residual oil	75.27
Solids and coal	88.44

[a]CO_2 arising from wood and other biomass used to generate electricity is not included in our calculations.

Source: Marland and Pippen (1990).

as travel demand has grown, so have associated environmental problems such as noise air and urban runoff pollution, traffic congestion and suburban sprawl. Transport's reliance primarily on fossil fuels has contributed significantly to the accumulation of both CO_2 and acid rain precursors, such as SO_x and NO_x, in the atmosphere (IEA, 1993). Energy use is a significant source of greenhouse gas emissions, contributing 57% of all anthropogenic sources (Scheinbaum and Schipper, 1993). Transport comprises a growing share of this total energy use in Organization of Economic Country Development (OECD) countries.

In this study, we analyse trends in CO_2 emissions from the passenger transport sector for the USA, Japan, France, former West Germany, Italy, UK, Denmark, Norway and Sweden, over the period 1973–92. We examine trends in emissions for four main modes, automobiles (which includes cars, light trucks and vans), buses, rail, air transport ('air') and, where significant two secondary modes (water and motorcycles). We include all major fuels used by each mode. Most previous studies have overlooked both the share of diesel (or even LPG) used by automobiles, as well as the important use of gasoline by freight vehicles. Elsewhere (Schipper, 1993a) we have shown that these omissions lead to serious errors in measuring the change in total fuel use by, and emissions from, passenger automobiles and light trucks. We then show how population growth, activity, mode shifts, fuel choices, fuel efficiency and load factors (number of persons per vehicle) affected the overall trends. Finally, we examine the policy implications of these trends and identify the potential for reductions in CO_2 emissions.

Background

The demand for passenger transport and mode choice are affected by many factors, including lifestyles, income, labour structure, cost of travel, time available for travel and urban development patterns. Increasing incomes result in higher car ownership and more driving (Webster *et al*, 1986a,b), while falling fuel prices encourage travel. While high fuel prices between 1973 and 1985 certainly restrained travel, since then real fuel prices have fallen in a majority of OECD countries (Schipper *et al*, 1993b). It is not therefore surprising if car usage in these countries has risen. Growth in population, while slow in OECD countries, magnifies the overall impact of all of these trends. Our basic method of factorialization identifies the role of these components of changes in CO_2 emissions, as well as those related to fuel mix, modal split, and the energy intensity of each mode, which was first carried out for energy demand by Schipper *et al* (1992) (see also Danielis, 1995).

Past studies on the transport sector show that energy use from transport is growing. Schipper *et al* (1992) identified effects of energy intensity, modal structure and activity on trends in passenger transport energy use in OECD countries and found that increasing passenger kilometres per capita and a shift toward the private automobile were the main factors driving up energy use in most countries, whereas increasing efficiencies counteracted this effect somewhat. They found that total energy use for travel increased 13% in the USA, 55% in a collective of six European countries and 76% in Japan over the period 1973–88.

Energy intensity can be defined in two ways: vehicle energy intensity, expressed as energy use in megajoules per vehicle kilometre (MJ/vkm), and modal energy intensity, measured as energy use per passenger kilometre (MJ/pkm). Overall vehicle intensity is determined by a given vehicle's engine fuel efficiency, the weight, size of the vehicle and features such as air conditioning and automatic transmission, while modal energy intensity is determined by vehicle energy intensity and load factor (number of persons per vehicle). We use modal intensity in this work because this gives a more meaningful indicator of energy use to move people rather than vehicles and allows us to compare travel in cars directly with that of other modes. Since the load factor itself is a function of many socioeconomic variables, this means that energy intensity is not a purely technological quantity.

The International Energy Agency (IEA, 1993) looked at technical economic and market potentials for alternative fuels, increased efficiencies and related implementation policies. Vehicle intensity of automobiles in the OECD countries in 1992 ranges from around slightly less than 3 MJ/vkm (Italy, France, Denmark) to slightly over 4 MJ/vkm (USA). With an average occupancy of 1.5 to 1.8 passengers per car as determined from national travel surveys (see IEA, 1993; Davis, 1994), this yields modal intensities from less than 1.5 MJ/pkm (Italy, France) to close to 3 MJ/pkm (USA, followed by Japan). Buses currently use 12 to 19 MJ/vkm, with vehicle occupancy ranging from 10 to 25 passengers per vehicle, yielding a much wider range of modal energy intensities than is the case for cars. At about 40% occupancy, which is average for most OECD countries, primary energy intensity for both electric and diesel passenger rail ranges from 1 to 1.5 MJ/pkm.

CO_2 emission factors, measured in grams of CO_2 released per megajoule (MJ) of fuel burned, vary with the type and chemical composition of fuel used to power any given activity. Average CO_2 coefficients for liquid fuels have been determined by laboratory tests and theoretical calculations (Marland and Pippen, 1990). Table 1 shows the main transport fuels in order of increasing CO_2 intensity (Table 1), or CO_2 emitted per unit of energy released. The choice between diesel and gasoline fuel involves a trade off between fuel intensity, which tends to be higher in gasoline engines of comparable size to diesel engines, and carbon intensity, which is higher for diesel fuel. Some alternative fuels which have lower CO_2 intensities are liquid petroleum gas, compressed natural gas and biomass (IEA, 1993), but these have not been used in significant quantities in the countries we studied.

Calculating CO_2 intensities for electric transport is more complicated than for liquid fuel-powered vehicles. The CO_2 intensity associated with electricity is a function of the mix of fuels used to generate the electricity (CO_2 emitted/ unit of energy of fuel used to generate electricity) and the efficiency of power generation, transmission and distribution (joules of primary energy per unit of final electricity consumption). Fuels for electricity (Table 1) include residual oil, natural gas, renewables (including biomass), coal and other solids that are counted with coal. Most renewable energy sources for electric generation, such as hydro, nuclear, geothermal and solar power have zero emissions at the point of generation, so these are not counted here.

Methodology

Data sources for our study consist of a collection of national travel, fuel use and vehicle surveys within OECD countries, as listed in the appendix of Schipper *et al* (1992), as well as in Schipper *et al* (1993a,b). The data include vehicle kilometres travelled, load factors, fuel consumption, energy consumption, vehicle stocks and vehicle efficiency, as well as economic and population statistics, such as gross domestic product (GDP), average income and population growth. Many of these LBL data are published in the Oak Ridge National Laboratory (Davis, 1994) in their annual *Transport Energy Handbook*. Our analysis is limited to motorized transport within national boundaries of each country.

End use analysis considers energy and emissions only at the point of consumption, whereas lifecycle analysis accounts for emissions and energy use resulting from fuel extraction, processing, distribution, vehicle manufacturing and end use. Lifecycle analysis models show that typically about 72% of greenhouse gases come from tailpipe emissions during vehicle operation, 17–18% come from fuel extraction, processing and distribution and 10% arise from vehicle manufacturing (IEA, 1993). End use energy and emissions are analysed here because they contribute the bulk of emissions (and changes in emissions) and because a lifecycle analysis is beyond the scope of this study. Moreover, since changes in the mix of fuels for travel to 1992 have been relatively small we would expect the differences in lifecycle emissions between these fuels to have little impact on overall CO_2 emissions.

Heating values (energy available per unit of a given fuel) are reported in two ways: gross and net. During the internal combustion process, a fraction of the energy contained in the fuel is lost to water vapour in the exhaust. The gross heating value accounts for the both the energy lost to water vapour and that which is available to the engine, whereas the net heating value represents only the latter. The net or lower heating value is reported by many country surveys, and can differ between 10 and 15% of the gross heating value. To account for all the CO_2 released per unit of fuel consumed, including that from incomplete combustion, we count the carbon released at the higher heating value. The carbon coefficients we apply, taken from Marland and Pippen (1990), are reported in grams of CO_2 per megajoule of energy at the higher or gross heating value of each fuel (in MJ per litre or kilogram of fuel). Therefore, we account for this implied loss of CO_2 by adjusting the calorific content of fuels as reported by each country to reflect the higher heating value of each fuel.

Having calculated the CO_2 emissions from each mode over time, we then analyse the impact of changes in terms of five components: activity, measured in passenger kilometres (pkm); structure, measured in modal shares of total pkm; CO_2 intensity, measured in tonnes of CO_2 emissions per pkm; energy intensity, measured in energy use per pkm; and fuel mix, measured in CO_2 emissions per unit of energy consumed for total activity. CO_2 intensity is a function of the last two components, fuel mix and energy intensity; energy intensity is, in turn, a function of fuel intensity and load factor. The individual effects of these components are modelled by letting each fluctuate while the others are held constant over time, thus depicting how CO_2 emissions might have changed if only one factor, such as fuel mix or energy intensity, had changed. This separates out effects that are principally socioeconomic, such as total travel and modal choice, from factors that have a strongly, technological component, such as energy intensity, or fuel mix.

It should be stressed that these components are not necessarily independent of each other. Since fuel prices are the dominant variable cost component of automobile use and a significant component of airline expenditures, lower fuel intensity reduces travel costs and thus raises the demand for travel on these modes somewhat, as well as lowering costs relative to those of alternative modes. Greene (1992) reported this feedback for automobiles as an elasticity of car use with respect to vehicle fuel intensity in a range of 0.05–0.15. For the USA this effect, though small, may not be negligible since the vehicle intensity of automobiles decreased by around 30% by 1992, while fuel prices were close to their 1973 levels in that year. For other countries, automobile vehicle intensities either increased or decreased by less than 10% and automobile modal intensities (MJ/pkm) increased, so there was little prospect for feedback. However, the roughly 50% decline in air travel intensity certainly contributed to lowering ticket costs, which in turn stimulated some travel.

Changes in emissions resulting from a change in one component are calculated by applying the respective index from Table 2, with 1973 as a base year. The total change in emissions is multiplicative of the first three indices (activity, CO_2 intensity and modal structure), while CO_2 intensity is additive of the last two components (energy intensity and fuel mix). These results identify the relative importance of each component of change in emissions, which can be useful to

Table 2 Equations used to model the societal and technological factors affecting percentage change in CO_2 emissions

Social and technological factors	% change in CO_2 emissions in year, i and mode, j
Actual emissions	$=\left(\sum_{j=1}^{n} C_{i,j} / C_{.73}\right)\cdot 100$
If only activity had changed	$=\left(\sum_{j=1}^{n} A_{i,j} / A_{.73}\right)\cdot 100$
If only modal structure had changed	$=\left(\sum_{j=1}^{n} (C/A)_{j,73}(S)_{i,j} / C_{.73}\right)\left(\sum_{j=1}^{n} A_{j,73}\right)\cdot 100$
If only CO_2 intensity had changed	$=\left(\sum_{j=1}^{n} (C/A)_{i,j}(A)_{j,73} / C_{.73}\right)\cdot 100$
If only energy intensity had changed	$=\left(\sum_{j=1}^{n} (C/E)_{j,73}(E/A)_{i,j}(A_{j,73}) / C_{.73}\right)\cdot 100$
If only fuel mix had changed	$=\left(\sum_{j=1}^{n} (C/E)_{i,j}(E)_{j,73} / C_{.73}\right)\cdot 100$

[a]C = grams (g) of CO_2, E = MJ of energy consumed, A = activity in passenger kilometres (pkm), s = mode share (pkm of mode j divided by total pkm of all modes), i = year, j = number of modes.
[b]C = grams CO_2/megajoule $(MJ)_k$ *total MJ consumed, where k = fuel type).

Source: The factorization method is explained in Howarth *et al* (1992) and Schipper *et al* (1992).

the policy maker concerned about such changes. Using the product of these indices to estimate changes in total emissions yields only a small residual with respect to our direct calculation of the actual emissions (see Howarth *et al*, 1991).

Results and analysis

General trends and comparison among countries

The USA was the highest per capita emitter of CO_2 in 1992, followed by Germany, Sweden, UK, Norway, France, Denmark, Italy and Japan (Table 3B). In 1992 the USA emitted 968 Mt CO_2, almost three times as much as all the European countries combined, and 3.80 tonnes per capita, more than three times as much as Japan (Table 3A, B, Figure 1). By far the most important reason for this difference has been the much higher level of per capita travel in the USA compared to the other countries. Differences in modal mix and energy intensity play a much smaller role, while differences in fuel mix are almost inconsequential

Trends in CO_2 emissions over time are surprising. Per capita emissions in the USA actually declined by 7% and total CO_2 slowly grew by 12% over the period, equating to a less than 1% annual growth. By contrast, per capita emissions in Europe grew an average of 56% over the period (Table 3D), with an average annual growth of 2.4% (Table 3F). Italy, Japan and Norway had the highest growth in per capita emissions (Table 3D), 95, 70 and 61% increase, respectively). Of the European countries, Denmark had the lowest growth in per capita emissions, with only a 3% change. Although Japan and Italy were some of the lowest per capita emitters in 1992, emissions in these countries have grown significantly since 1973. This has been a general trend among many of the countries studied. That is, the lowest per capita emitters generally had the greatest growth in per capita emissions over the period, shrinking the gap over time in per capita emissions between the USA and the other countries studied (Figure 3). As we shall see, growth in travel activity, principally in cars, was the main factor closing this gap. In every country, total emissions grew more than per capita emissions because of population

Table 3 CO_2 **emissions in OECD countries 1973–90**

	(A) Total emissions (Mt CO_2)					(B) CO_2 per capita (t CO_2/per capita)				
	1970	**1973**	**1979**	**1985**	**1992**	**1970**	**1973**	**1979**	**1985**	**1992**
USA	745	866	903	873	968	3.64	4.09	4.04	3.67	3.80
Japan	54	73	98	102	140	0.52	0.66	0.84	0.84	1.13
France	37	45	54	62	72	0.73	0.87	1.01	1.12	1.26
Germany	55	66	83	87	105	0.91	1.06	1.34	1.43	1.64
Italy	na	34	42	52	69	na	0.62	0.75	0.90	1.20
UK	41	51	56	63	80	0.74	0.92	1.00	1.12	1.37
Norway	3	3	4	5	5	0.68	0.79	1.07	1.20	1.27
Sweden	10	9	12	12	14	1.09	1.25	1.41	1.47	1.58
Denmark	na	5	5	4	6	na	1.08	1.09	1.02	1.11
EUR 7	na	214	256	287	350	na	0.90	1.08	1.20	1.41
	(C) % change in CO_2					**(D) % change in** CO_2 **per capita**				
USA	16	4	−3	11	12	12	−1	−9	4	−7
Japan	33	35	4	38	94	28	27	0	34	70
France	23	20	14	17	59	20	16	10	12	44
Germany	18	26	5	20	60	16	27	6	15	55
Italy	na	25	22	33	103	na	22	21	33	95
UK	24	9	14	26	55	23	9	12	23	50
Norway	19	40	21	9	74	16	35	13	6	61
Sweden	10	28	5	12	51	15	13	5	8	27
Denmark[a]	na	−12	−9	10	8	na	1	−7	9	3
EUR 7	na	20	12	22	64	na	19	11	18	56
	(E) Average annual growth (%)					**(F) Average annual growth per capita (%)**				
USA	5.2	0.7	−0.6	1.5	0.6	4.0	−0.2	−1.6	0.5	−0.4
Japan	10.1	5.2	0.7	4.7	3.5	8.6	4.1	−0.1	4.3	2.8
France	7.1	3.0	2.1	2.3	2.5	6.1	2.5	1.7	1.7	1.9
Germany	5.7	3.9	0.9	2.7	2.5	5.0	4.1	1.0	2.0	2.3
Italy	na	3.8	3.4	4.1	3.8	na	3.3	3.2	4.1	3.6
UK	7.5	1.4	2.2	3.3	2.3	7.2	1.4	1.9	3.0	2.2
Norway	5.8	5.7	3.3	1.3	3.0	5.1	5.1	2.0	0.8	2.5
Sweden	3.5	4.2	0.9	1.6	2.2	4.7	2.0	0.7	1.1	1.3
Denmark	na	−2.2	−1.5	1.4	0.4	na	0.2	−1.1	1.2	0.1
EUR 7	na	3.1	1.9	2.9	2.6	na	3.0	1.8	2.4	2.4

[a]Values are for 1988.

Source: This study and Schipper (1994).

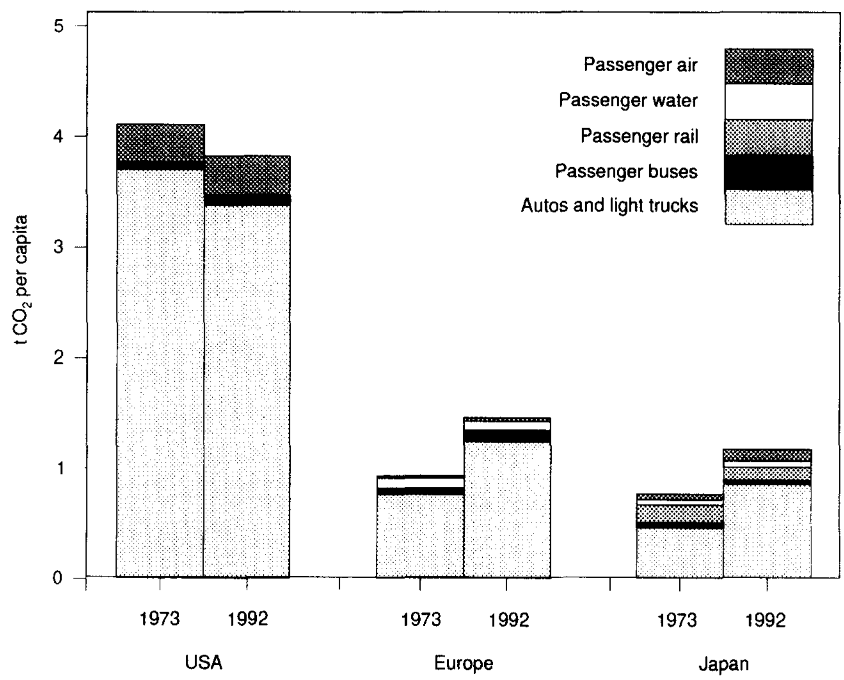

Figure 1 Per capita CO_2 emissions from travel: USA, Europe and Japan compared, 1973 and 1992

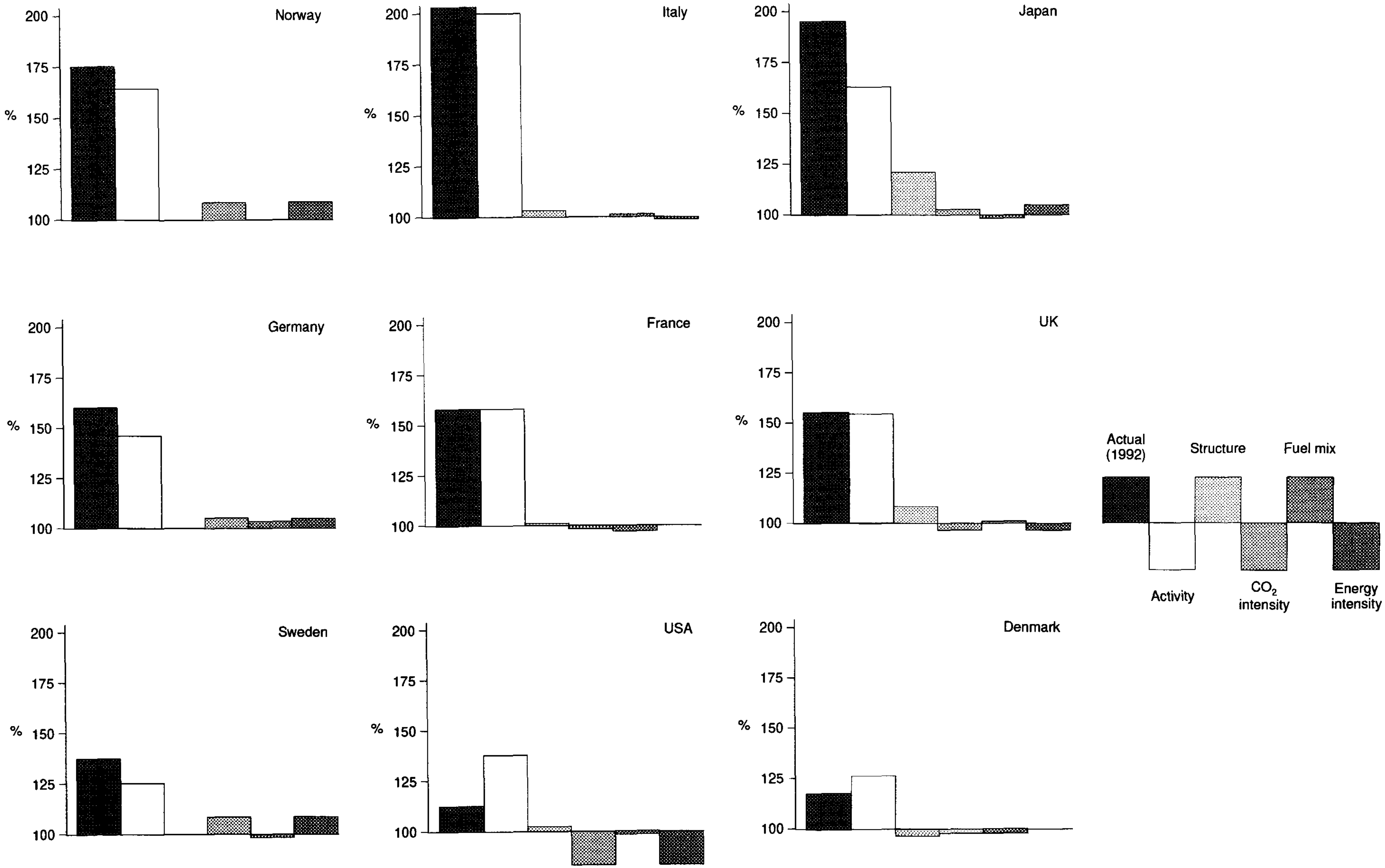

Figure 2 Actual and hypothetical emissions in 1992 relative to 1973 emissions[a]

[a]'Actual' growth in emissions by 1992 are depicted by the first bar in each graph. The remaining bars represent hypothetical changes in emissions as if only one variable, eg fuel mix, had changed, where values are 1992 emissions as a percentage of 1973 emissions.

Table 4 Hypothetical CO_2 emissions in 1990 as a percentage of 1973 emissions

	Actual CO_2 emissions (Mt/Mt73)				If only CO_2 intensity had changed			
	1973	1979	1985	1992	1973	1979	1985	1992
USA	100	104	101	112	100	100	89	82
Japan	100	135	141	194	100	110	101	103
France	100	120	136	159	100	106	104	98
Germany	100	126	133	160	100	107	110	105
Italy	100	125	152	205	100	106	113	100
UK	100	109	124	155	100	99	98	96
Norway	100	139	159	174	100	117	108	108
Sweden	100	115	121	135	100	106	113	110
Denmark	100	108	100	116	100	98	95	98
	If only energy intensity had changed				**If only modal structure had changed**			
USA	100	100	89	83	100	101	105	103
Japan	100	110	104	106	100	109	113	120
France	100	106	106	100	100	100	101	101
Germany	100	107	110	105	100	101	102	100
Italy	100	106	112	99	100	100	101	103
UK	100	99	98	95	100	102	105	108
Norway	100	117	108	108	100	99	101	100
Sweden	100	106	113	110	100	99	99	100
Denmark	100	97	95	100	100	98	96	96
	If only fuel mix had changed				**If only activity had changed**			
USA	100	100	100	99	100	105	113	136
Japan	100	100	98	99	100	113	125	162
France	100	100	98	101	100	114	131	159
Germany	100	101	100	100	100	116	118	146
Italy	100	101	101	101	100	118	135	199
UK	100	100	100	102	100	107	122	154
Norway	100	100	100	100	100	119	148	164
Sweden	100	100	99	99	100	110	112	125
Denmark	100	101	101	98	100	111	115	126

growth. This growth was generally less than 1% per year, and the change multiplies other changes by as little as 1.13 (Norway and France) to 1.16 (USA).

Although total and per capita annual emissions showed growth for the entire period, this growth was markedly slower after the 1973 oil shocks in most countries. Average annual growth in emissions is much higher for the period 1970–73 than for any other time period shown in Table 3E,F, including the entire period 1973–92 (Table 3E, F). For example, Tables 3E,F show that average annual growth of per capita emissions in Sweden was 4.7% between 1970 and 1973, but only 1.5% between 1973 and 1992 (Table 3F). In the USA, average annual growth in per capita emissions was 4% from 1970 to 1973, but from 1973 to 1992 average annual growth was approximately zero. The trend break is more dramatic if the analysis is extended back to 1960 or 1965, which we have done only for the USA, West Germany and Japan. The break was probably due to the two oil shocks of 1973 and 1979, which, in our data, were associated with reduced travel demand and a decline in the energy intensity of travel. This break in emissions was more prominent in the USA than in any other country because the decline in fuel intensity of US automobiles was so large.

Activity

Applying the formulae in Table 2 shows that increasing activity has been the main factor driving up energy use and subsequent CO_2 emissions between 1973 and 1992 (Table 4). Per capita passenger kilometres travelled have increased, on average, by 37% in the countries studied (Table 5). The most dramatic growth in passenger kilometres per capita was seen in Italy (100%), Norway (56%) and the UK (49%). In the UK and Italy, growth in travel overwhelmed the small declines in fuel intensity (Table 4 and Figure 2). More significantly, our calculations indicate that in the USA, emissions would have decreased by 17% if only energy intensity had changed, but increased by 36% if only activity had changed. In the end, this increase in activity outpaced the decrease in intensity, resulting in an actual net increase of 12%. In France, increasing activity was the sole factor in a 59% increase in emissions over the period. For the USA, some of the increase in activity is probably attributable to the slightly reduced costs of travel resulting from gains in efficiency, especially for automobile travel (Greene, 1992). In other countries, these effects were small, as we noted earlier.

Growth in travel is principally driven by growth in auto ownership (Webster *et al*, 1986a,b). One reason for this is that cars provide higher speed and more flexible travel than non-motorized modes or public transit. Further, growth in travel tends to be higher in countries that have increasing per capita car ownership levels from previously low per capita car ownership levels. Norway and Italy are two examples where rapid growth in automobile ownership accompanied rapid growth in travel (Tables 5 and 6). The USA, by contrast, began the 1970s with the highest car ownership and total travel, but experienced the second lowest

Table 5 Passenger kilometres per capita

Country	1973 (pkm/per capita)	1992 (pkm/per capita)	% change
Italy	6 696	13 385	100
Norway	7 782	12 134	56
UK	7 779	11 593	49
France	8 917	12 922	45
Germany	8 019	11 321	41
Japan	6 476	9 194	21
Denmark	10 130	12 290	17
Sweden	10 002	11 697	42
USA	19 602	22 188	13
Eur 7	7 911	12 253	55
Average (9)	9 489	12 969	37

Source: this study and Schipper (1994).

Table 6 Car ownership per thousand capita

Country	1973 (cars/1 000)	1992 (cars/1 000)	% change
Japan	134	315	135
Germany	275	499	82
Italy	242	452	87
Norway	231	377	64
France	274	417	52
UK	237	355	50
Sweden	303	410	35
USA	470	571	23
Denmark	265	322	21
Eur 7	259	429	65
Average (%)	270	425	77

Source: this study and Davis (1994).

growth in car ownership and the lowest growth in car travel per capita over the period.[1] However, the USA still had the highest per capita auto ownership and per capita travel at the end of the period, with 571 cars/1000 and more cars than people with driver's licences (Hu and Young, 1992). Although growth in auto ownership in the USA seems to have levelled off and may have reached saturation, passenger kilometres travelled continue to grow slowly.

Modal structure

Autos, which include cars, vans and household light trucks in this study, dominate the total share of pkm, especially in the USA where autos were responsible for 86% of the total passenger kilometres travelled in 1992 (Table 7A).[2] Rail and buses account for a much larger share of travel in Europe compared to the USA, but the automobile is still the dominant mode (75% or more of total travel). In Japan, the share of pkm is divided approximately equally between autos and rail; however, Japan's primary mode of travel has shifted from rail to autos over the period (Table 7A).

In most countries, modal structure shifted towards automobiles and airplanes and away from buses and rail (Table 7A). Growth in auto ownership and use was driven by growth in incomes and was magnified by increasing participation of women in the workplace and expanding suburbs (Schipper *et al*, 1989). Growth in air travel over the period has been driven by rising incomes and falling real costs of air travel (IEA, 1993). The calculations show that these shifts in modal structure increased emissions only slightly compared to increasing activity in most countries (Table 4), although a shift to the private auto may indirectly increase travel (Webster *et al*, 1986a,b) and therefore emissions, as discussed above. In Japan, a shift to cars and air travel, between 1973 and 1992, had a significant upward effect on emissions, increasing total emissions by 20%. In the UK, changes in modal structure increased emissions by 8%, due mainly to a modal shift away from buses (7.6% decrease) and towards autos (10% increase). Denmark is the only country where modal shifts towards buses and rail led to a clear decline in travel energy use and CO_2 emissions.

Shifts between modes can produce unexpected effects. CO_2 intensity for air travel in Japan fell from the most CO_2 intensive mode in 1973 to just below that of autos in 1992, decreasing by 34% (Table 7B). This is an unusual case where the ranking of energy intensities of the individual modes has changed over time such that a shift between modes in 1973 would have an opposite effect on CO_2 emissions than if the same shift occurred in 1992. In the USA, a similar effect occurred between 1973 and 1992. The average energy intensity of automobile travel fell while that for city buses and light rail travel increased to virtually the same as automobile travel by 1991 (Davis, 1994). Currently, cars are by far the most carbon intensive of the four modes, due mainly to their high energy intensity (Table 7B, C), followed by buses, air and rail in most countries. However, the foregoing examples show that it may be misleading to simply compare current differences in the CO_2 intensity between modes to predict the impact of modal shifts on emissions. Instead, one must consider the dynamics of modal shifts and trends in CO_2 intensity from each mode.

CO_2 intensity

According to our model, changes in fuel mix and energy intensity interacted to determine overall changes in carbon emissions per passenger kilometre (Table 4). Carbon intensity declined in the USA and the UK, mainly because of decreased modal energy intensities (Table 4). Declining CO_2 intensity decreased emissions 18% in the USA and 4% in the UK (Table 4). CO_2 intensity increased in the remaining countries, with Sweden and Norway having the most substantial increases, due to an increase in overall modal energy intensity in both countries (Table 4). The changes in CO_2 intensity were almost entirely due to changing energy intensity in all of these countries, while fuel mix fluctuated only slightly or remained constant.

Energy intensity

Modal energy intensity changes make up the most important component of changes in CO_2 intensity. Modal intensity

[1]The low rate of growth in automobile ownership in Denmark is probably explained by very high taxes on auto acquisition, taxes that add roughly 200% to the before-tax price of a new car.

[2]Household light trucks are clearly used the same as cars in the USA (Davis, 1994), representing over 20% of household vehicles. They also represent over 5% of personal vehicles in Denmark. In other countries they are much less important as household vehicles. Their contribution to travel is included in both countries.

Table 7 Modal shares, CO_2 intensity and energy intensity changes

		(A) Mode shares		(B) CO_2 intensity			(C) Energy intensity				
		1973	1990	1973	1992	%Δ			1973	1992	%Δ
USA							Autos	MJ/vkm	6.28	4.11	–35
	Autos	90	86	0.21	0.18	–15	Autos	MJ/pkm	3.07	2.63	–14
	Buses	4	4	0.06	0.06	11	Bus		0.79	0.90	14
	Rail	1	1	0.05	0.04	–26	Rail		1.81	2.12	17
	Air	5	10	0.33	0.18	–47	Air		4.92	2.74	–44
							Average		3.08	2.55	–17
Japan							Autos	MJ/vkm	3.88	3.71	–1
	Autos	36	50	0.17	0.18	–1	Autos	MJ/pkm	2.79	2.64	–1
	Buses	16	9.3	0.04	0.05	23	Bus		0.54	0.65	–2
	Rail	44	35	0.05	0.04	–14	Rail		0.34	0.42	0
	Water	1.1	0.5				Water		7.04	12.5	77
	Air	2.3	5.0	0.24	0.15	–36	Air		3.48	2.25	36
							Average		1.41	1.72	23
France							Autos	MJ/vkm	2.84	2.73	–4
	Autos	82	83	0.11	0.11	1	Autos	MJ/pkm	1.48	1.48	0
	Buses	7	6	0.05	0.06	36	Bus		0.61	0.83	36
	Rail	11	10	0.04	0.02	–64	Rail		0.36	0.33	–8
	Air	0	1	0.32	0.15	–54	Air		4.51	2.08	–54
							Average		1.31	1.34	2
Germany							Autos	MJ/vkm	3.46	3.22	–7
	Autos	78	83	0.15	0.16	7	Autos	MJ/pkm	2.05	2.19	7
	Buses	11	8	0.04	0.05	34	Bus		0.55	0.74	34
	Rail	10	8	0.08	0.06	–26	Rail		0.60	0.45	–24
	Air	1	1	0.30	0.22	–26	Air		4.17	3.00	–28
							Average		1.75	1.94	11
Italy							Autos	MJ/vkm	2.69	2.40	–11
	Autos	79.1	81.3	0.10	0.10	0	Autos	MJ/pkm	1.31	1.31	0
	Buses	10.3	11.4	0.04	0.04	–6	Bus		0.58	0.55	–6
	Rail	10.1	6.3	0.05	0.05	0	Rail		0.47	0.43	–7
	Air	0.5	0.9	0.44	0.36	–19	Air		5.98	4.93	–17
							Average		1.18	1.20	2
UK							Autos	MJ/vkm	3.67	3.19	–13
	Autos	77	87	0.14	0.13	–11	Autos	MJ/pkm	2.00	1.83	–9
	Buses	14	6.4	0.05	0.08	54	Bus		0.60	1.05	75
	Rail	8.1	5.6	0.13	0.04	–67	Rail		1.00	0.87	-12
	Air	0.6	0.7	0.31	0.15	–52	Air		4.60	2.13	–54
							Average		1.76	1.74	–1.2
Norway							Autos	MJ/vkm	3.35	2.93	–13
	Autos	77	80	0.11	0.12	1	Autos	MJ/pkm	0.54	1.58	1
	Buses	12	8	0.06	0.11	87	Bus		0.79	1.48	88
	Rail	6	5	0.02	0.03	37	Rail		0.80	0.92	16
	Water	0	1.2								
	Air	3	6		0.22		Air				
							Average		1.45	1.71	18
Sweden							Autos	MJ/vkm	3.33	3.07	–8
	Autos	83.6	79.3	0.14	0.15	12	Autos	MJ/pkm	1.81	2.03	12
	Buses	7.0	10.8	0.08	0.07	–4	Bus		1.15	0.99	–14
	Rail	5.7	7.2	0.03	0.01	–71	Rail		1.00	0.95	–5
	Air	0.9	2.7	0.28	0.24	–14	Air		3.86	3.22	–17
							Average		1.72	1.85	7.5
Denmark							Autos	MJ/vkm	3.00	2.62	–13
	Autos	80.8[a]	76.3	0.11	0.11	4	Autos	MJ/pkm	1.53	1.56	2
	Buses	10.1[a]	14.6	0.03	0.04	20	Bus		0.45	0.47	5
	Rail	6.0[a]	7.6	0.10	0.08	–21	Rail		1.11	0.85	–24
	Air	0.5[a]	0.7	0.26	0.11	–59	Air		3.8	1.56	–59
							Average		1.46	1.39	–4.5

Source: This study and LBL data published in Davis (1994).

[a]Values are for 1972 (1973 data not available).

remained approximately constant in most of the European countries, declined significantly in the USA and increased in Norway, Sweden Germany and Japan (Figure 2), although in Sweden and Germany, energy intensity trends reversed and began declining after 1988. In the USA, vehicle energy intensity for autos declined 35%, from 6.3 in 1973 to 4.1 MJ/vkm in 1992, and modal intensity fell from 3.1 to 2.6 MJ/pkm between 1973 and 1992 (Table 7C). Decreasing load factors, from 2.03 to 1.61 persons per vehicle (tabulated in Davis, 1994), dampened the effect of improved fuel economy in the USA and were the cause of higher energy intensities for rail and bus transport in many other countries. In Norway changes in energy intensity, holding structure, fuel mix and activity constant, increased CO_2 emissions by 8% (Table 4). Average energy intensity there increased by 18% (Table 7). In Norway, the energy intensity of buses increased by 88% and that of rail by 16%. Decreasing load factors were the most likely cause of these increases in intensity for both cases, since the physical efficiencies of rail and bus are not likely to have decreased in proportion to the observed increases in energy intensity (MJ/pkm). Energy intensity for autos and air travel actually decreased by 14 and 8% respectively; however, the net effect was a modest growth in overall energy intensity for Norway (Table 7C). In Sweden, increases in energy intensity pushed up emissions by 10%, holding other factors constant. While air, bus, rail and auto vehicle (MJ/vkm) energy intensities declined in Sweden, auto energy intensity per passenger kilometre increased 12% due to decreasing load factors. Since auto use has remained a significant share of the travel (80%) in Sweden, the result has been a net increase in total CO_2 emissions. Japan's average energy intensity increased by 23% over the period (Table 7), also due to declining load factors, which would have contributed to a 6% increase in CO_2 all else being equal.

The differences in energy intensities between countries, and within a single country between modes, have decreased over time. (Schipper *et al*, 1992). Most prominently, the significant decline in energy intensity in the USA narrowed the gap between energy intensity in the USA and that in the rest of the countries. However, US modal intensities there generally remain the highest. In fact, 1992 US automobile modal energy intensity was nearly twice that of Italy, the least energy intensive country, which was 1.2 MJ/pkm in 1992. Intensities of rail and bus travel in the USA are also generally higher than in Europe and Japan, but that for air travel is very close to the intensities in these other countries. In 1973 differences in energy intensities and modal structure had accounted for roughly half of the difference between per capita emissions in the USA and in the European countries; by 1992 the USA and Europe converged somewhat, leaving total travel as the most significant component of the difference between US and European emissions.

Fuel mix

A shift to diesel-fuelled automobiles and further electrification of rail systems are the main factors affecting fuel mix. Our model shows that overall fuel mix shifted to increase emissions slightly in the UK and Germany and in France, to decrease emissions by just 3%; changes in fuel mix had little effect in other countries (Figure 2). Although gasoline is still the main energy source for transport, the share of diesel fuel, which is more carbon intensive than gasoline, grew significantly in several countries. The use of coal for power generation increased significantly in Denmark and Italy as well; however since electric powered transport is a small part of total energy use, the effect on CO_2 was negligible. Diesel fuel in many countries has been priced below gasoline. Consequently, the use of diesel automobiles for private use has grown in many countries (Schipper *et al*, 1993a). For example, Italy had a fiscal tax policy favouring diesel fuel, which has resulted in the pump price of diesel fuel being half that of gasoline. Of the total energy use for transport in Italy, the use of diesel fuel surged from 0.6 to 23% of all final energy use for travel for automobiles and from 5 to 8% for buses over the period (Table 8). Diesel-powered autos and light trucks also became popular in Japan, increasing from 0.1 to over 7% of the total transport energy share. In France and Sweden, the increasing shares of diesel were more than offset by the tremendous growth in share of nuclear power generation.

Although diesel fuel releases more CO_2 per unit of energy than gasoline, diesel engines generally use less fuel per vkm than do gasoline engines. Consequently, a shift to diesel has not always resulted in an increase in CO_2 intensity (CO_2/pkm). For example, in Germany, 1990 gasoline vehicle intensity was 10.25 litres/100 vkm and that of the diesel powered fleet was 8.30 litres/vkm (a 19% difference) (Table 9). Accounting for the difference in carbon content between the fuels yields equal amounts of carbon emissions per vehicle kilometre (0.21 tonnes of CO_2 per 1000 vkm) for both diesel and gasoline vehicles. In Italy, diesel vehicles were 7% more energy intensive than gasoline and 22% more CO_2 intensive per vehicle kilometre in 1973. However, these figures fell dramatically over the period leaving diesel and gasoline vehicles at equal CO_2 intensities (at 0.18 tonnes CO_2/vkm) in 1992.

Influences of income, fuel prices, and fuel intensity on trends in CO_2

Most observers attribute higher incomes as the driving factor behind increased ownership and auto use (Webster and Bly, 1986a,b; see also Sterner, 1990, for a review of a variety of economic models of automobile use). This has led to many of the observed increases in total CO_2 emissions. Additionally, increased auto ownership led to a decline in the relative importance of local and intercity rail and bus travel, although per capita travel on these modes has increased in Europe. Comparison of price indices of fuel use with those for local transit shows the latter increased far more than the former in most countries, as Schipper *et al* (1993b) noted.

Trends in energy intensity and activity may, in part, be explained by differences and trends in fuel prices and taxation policies among the countries. Europeans pay three times as much for fuel as do Americans (Schipper *et al*, 1993a, 1993b; prices are given in Davis, 1994). Most of the differences in fuel prices between countries are due to differences in taxation levels (Schipper and Eriksson, 1995). Therefore, it is not surprising that Americans pay the least in fuel and automobile taxes, and also own the most cars, drive the most, and have the most fuel intensive cars. Conversely, Italians pay the most in car and fuel taxes and also have the lowest energy intensity and low per capita emissions. Further, Europeans, on average, own roughly two-thirds as many autos and drive 40% less per capita than do Americans (Schipper *et al*, 1993b).

Although fuel prices vary among countries, the budget share devoted to fuel expenditures among the countries seems to remain roughly constant. In some cases, there is a trade off made between distance travelled and energy intensity of travel in countries faced with higher fuel prices. For example, the Japanese drive less, per capita, than any other country (Table 4) but have relatively high fuel intensity (Table 7A), while Italians have very high levels auto ownership and travel demand but low fuel intensity (Tables 5, 6,

Table 8 Fuel shares in Denmark, Japan, UK and Germany

	Fuel shares (% of total MJ) 1973	1992		Electricity shares (% of electricity) 1973	1992
Denmark[a]					
Gas, autos +ltr	81.51	74.12	Oil	63.8	5.2
Gas, bus	0.11	0.02	Gas	0.0	3.5
Diesel, autos + ltr	2.05	9.46	Coal	36.1	87.7
Diesel, bus	2.45	4.40	Wood, waste, renewables	0.0	2.2
Diesel, rail	4.14	3.87	Nuclear	0.0	0.0
Electricity, rail	0.49	0.80	Hydro	0.0	0.0
Res oil 2-5, ship	na	0.02	Solar/wind/other	0.0	1.4
Diesel, ship	na	0.01			
Jet fuel, air	1.35	0.84			
Japan					
Gasoline, autos	64.2	65.4	Oil	75.2	26.7
Gasoline, bus	0.8	0.0	Gas	2.2	19.7
Diesel, autos	0.1	8.6	Coal	13.2	14.9
Diesel, bus	5.3	3.5	Wood, waste, renewables	0.0	0.0
Diesel, rail	2.2	0.6	Nuclear	2.8	33.7
Diesel, water	5.5	3.8	Hydro	6.3	4.1
Electricity, rail	8.6	8.0	Solar/wind/other	0.3	0.9
LPG, autos	7.6	3.5			
Jet fuel, air	5.6	6.5			
UK					
Gas, autos	88.7	87.9	Oil	25.5	8.4
Gas, bus	0.0	0.0	Gas	1.3	1.4
Diesel, autos	0.5	3.7	Coal	62.7	64.6
Diesel, bus	4.8	4.2	Biomass	0.0	0.4
Diesel, rail	3.4	1.6	Nuclear	10.1	24.5
Electricity, rail	1.2	1.1	Hydro	0.5	0.5
Jet fuel, air	1.5	1.5	Solar/wind/other	0.0	0.1
Germany					
Gas, autos + ltr	86.4	76.8	Oil	12.7	2.7
Gas, bus	0.5	0.3	Gas	10.4	9.1
Diesel, autos + ltr	5.0	16.0	Coal, coke	67.7	51.1
Diesel, bus	3.0	2.8	Wood, waste, renewables	1.0	1.4
Diesel, rail	2.4	0.7	Nuclear	3.5	32.5
Electric, rail	1.1	1.1	Hydro	4.7	3.2
Jet fuel, air	1.4	1.3	Solar/wind/other	0.0	0.0

[a]Values are for 1972 (1973 data not available).

7A). As a result, Europeans end up paying roughly the same share of their incomes in driving costs as Americans do, through a combination of lower distance travelled per capita (or per household) and less fuel intensive vehicles, as shown in Schipper *et al* (1993b).

The gap between the fuel intensity of the autos Europeans and Japanese drive and those Americans drive has narrowed significantly as fuel intensity in the USA has declined over the past two decades (Schipper *et al*, 1993b). Interestingly, fuel intensity of Europeans cars has not declined much over time. This is a result of significant increases in size, weight and power of the fleets in Europe and Japan (Schipper *et al* 1993b). Important technical improvements in engine fuel efficiency occurred in both the USA and Europe. However, in Europe, increases in automobile fleet weight and power nearly offset these improvements, and in the USA, both weight and power increases and an influx of light trucks resulted in a stagnation of test fuel economy after 1982 (Davis, 1994). These developments are not surprising. Incomes in Europe in 1992 were higher than in 1973; real fuel prices surged upward for only two relatively brief periods, and by the late 1980's, had reverted near to 1973 levels in most countries. The increased share of lower-cost diesel fuel also contributed to the stagnation of real fuel prices (Schipper *et al*, 1993b). Thus real fuel costs of driving 1 km in 1992 were lower than or about the same as they were in 1973 in all countries except Germany, Sweden and Norway. Finally, as many as two-thirds of new cars in the UK and one-third in Germany and Sweden were provided by employers to employees. Such schemes require the beneficiaries to pay a nominal increase in their income tax, usually far less than the value of the benefit they receive, particularly since they usually receive free gasoline. Schipper and Eriksson (1995) and Schipper *et al* (1993a) (and references therein) found that company cars tended to be larger and are driven more than truly private cars.

Through the late 1980s, however, the major exception to this upward trend in automobile weight and power was the USA where cars were already large and powerful in 1973

Table 9 Vehicle CO_2 and energy intensity of gasoline versus diesel automobiles in selected countries

	Tonnes CO_2/1000 vkm 1973	1992	Litres/100 vkm 1973	1992
Italy				
Gasoline	0.20	0.18	8.47	7.52
Diesel	0.24	0.18	9.09	6.67
	1978	**1990**	**1978**	**1990**
Germany				
Gasoline	0.25	0.21	10.73	10.25
Diesel	0.24	0.21	9.50	8.30

and where fuel economy standards (CAFE) were imposed. Although the exact roles of CAFE versus higher fuel prices in provoking the observed changes in fuel intensity in the USA is contentious (Schipper *et al*, 1993b; Greene, 1990), it is notable that no country in Europe saw anywhere near the decline in fuel intensity (or automobile fuel use per capita) experienced in the USA. Therefore, it is hard not to credit the CAFE standards with some of the change.

Recent trends in travel and CO_2 emissions: a cause for concern?

The foregoing analysis showed that increased travel contributed to increased per capita CO_2 emissions for travel in every country studied. To summarize, modal shifts also increased emissions in almost every country, while decreased energy intensities had a very small effect on energy use except in the USA. Fuel shifts had a very small impact on emissions. Virtual stagnation in the US car fuel economy means that rising activity is increasing CO_2 emissions from travel in the USA, while more rapid increases in activity and continued modal shifts are pushing up CO_2 emissions in Europe and Japan. Thus none of the components analysed here is contributing to significant CO_2 restraint at present.

Not surprisingly, this situation has led to concern from national authorities (Transport and CO_2 Committee, 1994; Royal Commission, 1994) as well as from the Intergovernmental Panel on Climate Change Working Group II (IPCC, 1990; see also Michaelis *et al*, 1995). Given the trends we have observed, what might restrain growth or even reduce CO_2 emissions from travel? Restraining or reducing CO_2 emissions could result from many combinations of changes in all of the factors we analysed, including adoption of fuels with few or no CO_2 emissions, significant declines in energy intensities (including increases in load factors as well as technological improvements to vehicles), shifts to less energy intensive modes, or reductions in travel.

Alternative fuels

One way to significantly reduce CO_2 emissions from transport would be to use renewable or non-fossil-based fuels (Sperling, 1988; see also the review of Michaelis, 1995). For example, electricity for electric vehicles or to make hydrogen fuel, when generated from renewable or nuclear energy, would have very few associated CO_2 emissions, though issues of costs and other environmental concerns must be addressed (Sperling, 1995). Much has been debated about the full fuel cycle impact on emissions of each alternative (Delucchi, 1991), and there are many promising options. But there is still much debate about the costs of alternatives to petroleum based fuels, as well as few no definitive observations of the full consequences for travel, fuel use and emissions of a significant fuel shift away from petroleum based fuels. For example, electricity and natural gas currently offer lower operating costs than gasoline in the USA and Europe. Would drivers using these fuels drive more? We will gather experience with these and other alternatives in the coming years.

Further improvements in fuel economy

There seems no question that further improvements in automobile fuel economy are possible (Schipper, Meyers *et al*, 1992, and references therein; NRC, 1993), but these are taking place only very slowly in Europe and not at all in the USA. Controversy exists over both what a given technical improvement would cost relative to fuel saved, and whether new policies (standards, fuel taxes, etc) are required to stimulate both automobile makers and consumers to adopt these changes. Undoubtedly new technologies will continue to reduce fuel intensity. The issue is how much these improvements will be offset by increases in car weight and performance.

Restraining travel demand and modal shifts

Although technical options to reduce energy use and emissions have been effective in the past, the fact that increasing activity outpaced improvements in fuel economy in every country indicates that consideration might be given to modifying travel demand or stimulating a shift back to less energy-intensive modes (Kaageson, 1993). However, CO_2 emissions are only one of several externalities that arise from transport. Others include safety, air pollution, noise, congestion and possibly the risks of importing oil for transport and other uses. Strategies to mitigate these problems may also reduce CO_2 and vice versa; however the priority that should be given to each problem relative to the others is an issue to be addressed elsewhere.

Changes in the pricing of transport to reflect the various externalities associated with travel could affect the level of demand and mode choice, and in turn reduce CO_2 emissions. Some schemes aimed at reducing travel demand include road pricing, congestion pricing and various types of VMT (vehicle miles travelled) taxes (NRC, 1994). Charges levied on fuels themselves to reflect pollution and health costs could have profound effects on travel. Small and Kazimi (1994) estimate that the present health costs of air pollution from automobiles in Los Angeles may be as high as the equivalent of US\$0.02/km or about US\$0.60/gallon. Compared with a retail fuel price of US\$1.25/gallon, this would represent a significant increase in driving costs and would undoubtedly affect automobile use. Changes in the way parking provided by employers is taxed, or changing the coupling between the cost of an individual's car insurance and the distance that individuals drive, could also raise the variable cost of using cars.

Internalizing environmental costs through pricing policies will almost certainly lower demand for travel and encourage more efficient travel (Schipper and Eriksson, 1995), Further, these taxing mechanisms are perhaps the most economically efficient way to deal with CO_2 emissions as well as the other problems associated with passenger transport (Baumol and Oates, 1988) because they stimulate travellers to choose from among a variety of technical and behaviour options to respond to the costs their externalities impose on others However, the correct level and mechanism of pricing and the extent of the resulting change in travel demand and modal mix are all subjects of ongoing debate.

Changes in urban form and density could also lead to less travel, but exactly how or how much is controversial, as Dunphy and Fischer (1994) point out. These strategies may have considerable merits in their own right, but they do not address CO_2 directly. Nevertheless, if such strategies restrain motorized travel or encourage more efficient modes, they will lead to restraint in CO_2 emissions.

Taxes aimed directly at CO_2, such as fuel taxes or changes in new car taxes which reflect the CO_2 emissions per unit of fuel, would affect the cost of vehicles and the cost of travel and possibly reduce emissions. In order to reduce emissions, it is important that fuel taxation levels are differentiated to reflect the relative carbon contents of various fuels, thus raising the cost of travel on all modes in proportion to the CO_2 intensity of each mode. This creates an incentive to travel less or travel on less energy intensive modes, an incentive not found in programmes to stimulate alternative fuels or fuel efficiency through regulations alone. Greening *et al* (1995) modelled a variety of CO_2 tax levels for the USA, using cross-sectional household data, and estimated in the short run that a 50% excise tax on gasoline would result in a 10% decline in greenhouse gas emissions from household vehicles. The Nordic countries have imposed modest CO_2 taxes on fossil fuels, although the CO_2 tax is small compared to other taxes already imposed on road fuels (Schipper and Eriksson, 1995; Magnusson and Braendel, 1991). Consequently, the effects of this CO_2 tax alone are expected to be small in those countries, but the tax could stimulate use of fuels with lower CO_2 emissions. In Sweden, the Transport-CO_2 Delegation is currently developing a plan to hold emissions from the transport sector constant through the early part of the next century (TOK, 1994). They seem to favour a carbon tax embedded in the price of road fuels, but they also point to a variety of measures aimed at bolstering collective transport, and they discuss measures that might reduce or restrain growth in travel as well. They also recognize that the tax treatment of company cars works against their goal. It remains to be seen whether other countries in Europe, and above all the USA, with much lower fuel prices, will follow suit.

In the final analysis, the value to society of restraining CO_2 emissions is still unclear. This makes it difficult to estimate how much fuel switching, fuel efficiency, modal switching, changes in travel, and changes in urban form could or should contribute to reduced emissions. This indicates a need to confront the CO_2 externality with a menu of policies that address all of these components of CO_2 use in concert with other problems facing transport.

Conclusion

In all the countries studied, annual CO_2 emissions from travel increased over the period of study, with Italy having the greatest increase and the USA the least. In 1992, the USA emitted three times as much carbon per capita as any other country, and Japan emitted the least carbon per capita. In all cases, increasing activity was the main factor in the increase of annual carbon emissions, but modal shifts, and increasing energy intensity and fuel switching in general raised CO_2 emissions as well. Declining energy intensities had a marginal impact, except in the USA where growth in CO_2 emissions was restrained significantly. By 1992 per capita CO_2 emissions from travel were rising in virtually all countries studied. If CO_2 emissions from travel are to be restrained, policies that affect all the components of travel we analysed should be considered.

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